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UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. Bennett, Chief

SEDIMENTATION IN SAN CARLOS RESERVOIR GILA RIVER, ARIZONA

By

Eldon M. Thorp
Geologist
Albuquerque, New Mexico

and

Carl B. Brown
Sedimentation Specialist
Washington, D. C.

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Prepared under the auspices of
Subcommittee on Sedimentation
Federal Interagency River Basin Committee

In cooperation with
Corps of Engineers, Department of the Army
Bureau of Reclamation, Department of the Interior
Gila Water Commissioner

SCS-TP-91

Washington 25, D. C.
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COOLIDGE DAM — SAN CARLOS RESERVOIR

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ABSTRACT

San Carlos Reservoir on the Gila River in southeastern Arizona is a major economic unit in the irrigation agriculture of the State. The multiple-dome dam, largest of its type in the United States, cannot be raised because of structural design; therefore, the life of the reservoir will be determined almost entirely by the rate of sediment inflow. Three sedimentation surveys have been made on San Carlos Reservoir, the latest being of a high order of accuracy. This permitted a comparison of sedimentation rates as of 1935, 1937, and 1947 and also served to correct minor inaccuracies of earlier surveys. The 1947 survey also produced the first good contour map of the entire reservoir to crest level. The reservoir had lost 57,494 acre-feet, or 4.54 percent of its total original capacity of 1,267,447 acre-feet at the time of the 1947 survey. The storage loss was 0.25 percent annually and the indicated rate of sediment production from the drainage area was 24.5 acre-feet per 100 square miles annually. During the entire period of record (1928-47) the sediment content of the inflow by volume was 1.24 percent.

Stream flow measurements are available at or near San Carlos site since 1896, and analyses of trends indicate subnormal inflow since 1942. If the future average inflow equals the long-term historic flow at San Carlos site and if watershed conditions continue as at present or deteriorate further, it is believed that the measured annual sedimentation rate of 3,161 acre-feet should be raised to about 5,000 acre-feet for estimation of long-term average depletion of capacity. Reasons for increasing the rate to 5,000 acre-feet annually are: below normal runoff during period of sedimentation in San Carlos Reservoir, increased diversion of sediment to irrigated lands during this subnormal runoff period, and greatly increased growth of salt cedar, baccharis, and other vegetation in channels and on floodplains of the Upper Gila. If a long-term average rate of 5,000 acre-feet per year prevails in the future, another 112 years (from 1947) will elapse before the reservoir capacity is depleted by 50 percent.

INTRODUCTION

This report summarizes the results of sedimentation surveys of San Carlos Reservoir, impounded on the Gila River by Coolidge Dam, in Gila, Pinal, and Graham Counties, Arizona.

Sedimentation surveys were made in 1935 and 1937 by the Soil Conservation Service and in 1947 under the auspices of the Sedimentation Subcommittee, Federal Interagency River Basin Committee, by the Corps of Engineers, Los Angeles District, and the Soil Conservation Service. The Bureau of Reclamation and the Gila Water Commissioner provided financial assistance to the above agencies in the 1947 survey. The results of the surveys were computed and this report was prepared by the Soil Conservation Service.

The volume, distribution and character of sediment in San Carlos Reservoir at the date of each survey are discussed. The engineering aspects of the several surveys are described in some detail to facilitate future resurveys. All data from earlier surveys have been recomputed on the basis of the more detailed and accurate mapping of the 1947 survey. The data included here, therefore, differ from and supersede those previously published.

The characteristics of the drainage area are summarized from the standpoint of their influence on the rate and distribution of sediment production. The runoff and water inflow during the periods between sedimentation surveys is given and compared with long-term flow characteristics of the Gila River and the probable long-term rate of sedimentation. The history of the San Carlos irrigation project and the use of water stored in San Carlos Reservoir are briefly described.

COOPERATION AND ACKNOWLEDGMENTS

The first sedimentation survey of the San Carlos Reservoir was made by a field party of the Soil Conservation Service under the direction of Raymond C. Becker in January-May, 1935. The aid extended by C. J. Moody, project engineer of the Indian Irrigation Service at Coolidge Dam, in furnishing original maps of the reservoir for this survey, is acknowledged. D. G. Butler, superintendent of Coolidge Dam at that time generously extended the courtesies of his camp and office for use of the field party.

The Soil Conservation Service made a second complete survey below elevation 2,460 in December 1936 and January 1937. This survey was under the direction of Louis M. Seavy.

The 1947 survey was made under an agreement worked out through the Sedimentation Subcommittee, Federal Interagency River Basin Committee,

for joint financing by the Corps of Engineers, Bureau of Reclamation, Soil Conservation Service, and Gila Water Commissioner. As described subsequently, ground control and stereoprojection mapping from aerial photographs was carried out by the Los Angeles District, Corps of Engineers. Sounding of the pool area, compilation of the final map, planimetering, computing and preparation of this report was done by the Southwest Region, Soil Conservation Service, Albuquerque, N. M., under the supervision of the writers. The aid of Mr. Sam Turner, of the Ground Water Branch, U. S. Geological Survey, in providing data on inflow, ground water and consumptive use in the Safford Valley, is gratefully acknowledged.

HISTORY OF SAN CARLOS PROJECT

The San Carlos Indian irrigation project was authorized by the legislative act of June 7, 1924 (43 Stat. 475-476). Known as the San Carlos Act, it authorized construction of Coolidge Dam on the Gila River to impound water for irrigation storage and also merged a large part of the Florence-Casa Grande project with the San Carlos project. Thus a total of 100,546 acres is included, of which 50,000 acres are Indian lands within the Gila River Reservation, and 50,546 acres are privately owned lands in the Florence-Casa Grande Valley. The lands thus included were designated by the Secretary of the Interior on April 25, 1928, and August 9, 1934. A third designation was made by the Indian Irrigation Service on May 12, 1936. In addition to the San Carlos project, approximately 4,328 acres of private and Indian lands have water rights from San Carlos Reservoir as well as return flow rights.

The water rights to the project were defined by "Globe Equity No. 59," a decree entered on June 29, 1935, in Federal District Court. This gave immemorial first priority to 35,000 acres of Pima Indian land within the project; 1,000 acres in the San Carlos Reservation, and varying priority rights dating from 1868 to 1921 between privately owned lands in the San Carlos project and lands in the Upper Gila Valley above the reservoir. The decree also gave the right to store 1,285,000 acre-feet of water in San Carlos Reservoir at all times.

Under the decree a water commissioner was appointed on January 1, 1936, to administer water releases, collect assessments of 13 cents per acre, and make reports on water distribution, analysis of expenditures, and presentation of all hydrometric data for related periods. The water commissioner has an office in Safford, Arizona, and in addition to his local assistants, has representatives in Thatcher, Duncan, and Hayden, Arizona. The San Carlos Irrigation and Drainage District has a cooperative agreement with the U. S. Geological Survey, Water Resources Branch, to provide provisional records of river gaging stations necessary for execution of the decree. A resident engineer of the U. S. Geological Survey is detailed to Safford for that purpose.

Coolidge Dam was built in 1927-28 and water impoundment started November 15, 1928. Diversion of releases from San Carlos Reservoir is

made at Ashurst-Hayden Dam above Florence, Arizona, and Sacaton Dam near Sacaton, Arizona. Parshall flumes are used at these diversion dams to measure flow passing them. Besides these two gravity diversions, a large number of turbine pumps are operated to augment irrigation water supply and to provide adequate drainage.

For the 52-year period 1896-1947 the average annual stream flow at the San Carlos Reservoir site was 346,712 acre-feet. However, since 1942 the inflow into San Carlos has fallen far below the long term average.

THE DAM AND RESERVOIR

Location. San Carlos Reservoir, created behind Coolidge Dam, is located in southeastern Arizona. The dam is in Section 17, Township 3 South, Range 18 East. Nearest cities are Globe, 28 miles northwest, and Safford, 60 miles east. The dam forms a portion of the boundary between Gila and Pinal Counties. The reservoir proper lies within Pinal and Graham Counties. The reservoir receives its water from the direct flow of the Gila River and a major tributary, the San Carlos River, which enters the reservoir from the north about 8 miles above the dam.

Date of completion. Construction of the dam was started in January 1927, and completed October 25, 1928. Storage of water was begun on November 15, 1928, as determined by cessation of flow at the stream gage located just below the dam. Previously the starting date of storage was erroneously reported as October 25, 1928.

Description of the dam. Coolidge Dam is a multiple-dome concrete structure and is the largest of its type in the United States. Each of its three domes has a base span of 180 feet at which the thickness is 28 feet. The thickness decreases to 4 feet at the top (See frontispiece). The original river bed elevation at the dam was 2,308 feet above mean sea level. The dam rises 205 feet to the spillway sill, elevation 2,513 feet, and an additional 44 feet to the roadway on top for a total height of 249 feet. The length of the dam including spillways is 850 feet.

Spillway and gates. On each side of the dam is a concrete spillway having a sill elevation of 2,513 feet. Each spillway has three gates, 50 feet wide and 10 feet high when raised to full position. These gates rise automatically with increasing water surface above sill level. When fully gated, the maximum storage capacity is reached at elevation 2,523 feet.*

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*In earlier reports the spillway crest was reported as 2,523.5 feet. A rechecking of levels in 1947 established the correct elevation to be 2,523.0 feet.

Outlets. Two penstock openings provide for release of water for irrigation. These also furnish water simultaneously for turbine power to generate electricity. Below the lowest penstock outlet level (2382.63 feet) is the dead storage pool.

Capacity of spillways and penstocks. The combined spillway capacity with gates lowered is 120,000 cubic feet per second. Penstock capacity at water elevation 2,523 feet is rated at 3,860 cubic feet per second, but maximum safe operation is about 2,000 cubic feet per second. Thus maximum safe release for all outlets combined is approximately 122,000 cubic feet per second.

Datum. All elevations mentioned are adjusted to mean sea level, 1927 North American datum.

Reservoir. The original storage capacity adjusted to the 1947 map standard was 1,267,447 acre-feet at elevation 2523. In earlier reports this capacity was given as 1,247,999 acre-feet (4). Original and present surface area at spillway elevation is 19,581 acres. This was previously report as 18,847 acres (4). In January 1947 the capacity was 1,209,953 acre-feet. Thus, between November 15, 1928, and January 22, 1947, (18.19 years) the capacity loss was 57,494 acre-feet. This represents a loss of 4.54 percent of the original capacity, or 0.25 percent annually.

The length of San Carlos Reservoir, measured from the dam to crest elevation in the Gila River channel near Calva, is 22 miles. Length of the principal arm of the reservoir, which extends up into the San Carlos River channel, is about 8 miles. Near the dam, the reservoir is 0.3 mile wide and the maximum width of 3 miles is reached about 4 miles upstream.

Operation and use. Storage of water in San Carlos Reservoir is primarily for irrigation of the San Carlos project. A secondary purpose is to generate electric power. Flood protection was not a planned function however, reservoir operation wherein flood waters are stored above pre-flood water levels lessens the frequency of high flood discharges in the river downstream of the dam and thus yields incidental flood control benefits. All stored water has decree rights and is released when needed and if available in carefully measured flows.

Power generation is subordinate to irrigation requirements and is curtailed if storage is low. The power plant contains two generators having a combined output of 2,400 kilowatts. Power generation has been intermittent and often stopped for long periods because of complete drawdowns.

HISTORY OF SURVEYS

Original survey. A topographic and cultural survey of the Gila River Valley was made in 1914 and 1915 under the direction of C. H. Southworth for the Indian Irrigation Service. The survey, which was made primarily for use in connection with the adjudication of water rights in the Gila Valley, covered the entire area of San Carlos Reservoir. This survey was made by plane table on a scale of 1,000 feet equals 1 inch with contour intervals of 5 feet on the valley floor and 10 feet on the valley slopes. Mr. Southworth in a letter to the late B. P. Fleming of the Soil Conservation Service in 1935 stated that "while we endeavored to keep our topography fairly accurate, yet the object of the survey (1914) was to map irrigated and previously irrigated areas and only sufficient detail of topography was taken to determine the limitations of the irrigable areas. This circumstance might possibly give rise to erroneous conclusions." Subsequent comparisons have shown that the original maps were comparatively accurate on the open valley floor but were considerably generalized on the steep dissected valley slopes adjacent to irrigable areas.

1935 Survey. Field work of the 1935 survey involved establishing a triangulation net of 31 stations, expanded from 7,300-foot base line, and secondary control by stadia, tied to the triangulation system. In the lower flooded section of the reservoir 40 ranges were established across the lake at intervals of approximately 1,000 feet, along which systematic soundings were taken on top of the sediment deposits.

In the upper reaches of the flooded area contours were mapped on the surface of the sediment deposits from numerous elevations established by soundings. The location of soundings was obtained by plane table and transit intersection from adjacent triangulation stations. In the upper part of the basin above backwater stage at the time of survey, contours were mapped by stadia traverse tied to triangulation stations.

Both the underwater mapping based on sounding and the exposed surface mapping of this survey were confined to the surface of the sediment deposits and did not extend to the valley slopes. The original capacity of the reservoir was determined from the Indian Irrigation Service maps made prior to construction of the reservoir. Contours mapped on the surface of the sediment deposits in 1935 were tied into contours of the old maps along the valley slopes. Although field checking of the old maps at that date revealed errors and generalizations in the original contours, it was considered that resurveying the steep and rugged valley slopes to spillway contour 2,523 was not possible in view of the time and funds then available.

The 1935 capacity was computed by deducting the area difference at each contour from the original area to develop a new contour area table as of 1935. It follows that such error as was inherent in the valley slope topography of the original survey was also reflected in the 1935 survey both in the total capacity and in the accumulative capacity to

any given elevation. On the other hand, because the original contours were more accurate on the valley floor where the sediment was deposited than on the valley slopes, the differences in area and hence capacity loss between the original and 1935 surveys were relatively more accurate than the accumulative area or capacity shown by either survey.

1937 Survey. At the request of the Gila Water Commissioner a resurvey of the storage capacity of the reservoir up to contour 2,460 was made by the Soil Conservation Service between December 1, 1936, and January 22, 1937, primarily for the purpose of developing an accurate capacity curve for reservoir operations. This survey, using the 1935 triangulation system as a base, involved resounding all portions of the reservoir below the then existing water level (about contour 2,395) and plane-table mapping of exposed sediment deposits and valley slopes up to contour 2,460. This survey showed considerable differences in areas enclosed by contours above elevation 2,435, the prevailing upper limit of mapping in 1935. These differences, due to generalizations in the original maps, showed that the reservoir capacity below elevation 2,460 was actually greater in January, 1937, than it was determined to be in 1935 by the previous survey, which depended on original maps for computations between contours 2,435 and 2,460. This survey as well as that of 1935 provided contours on the surface of the sediment that could be used in the adjustments made after the 1947 survey, as described below.

1947 Survey. As a result of successive years of low flow (1943-46) following the high flows of 1941 and 1942, the water stored in San Carlos Reservoir was exhausted by June, 1946. Observation indicated the obvious need for a resurvey to correct the capacity curve so as to permit equitable future operation of the reservoir in the interests of all water users. On the appeal of the late C. A. Firth, Gila Water Commissioner, to the Soil Conservation Service for a resurvey, and because of the interests of several Federal agencies in the conservation, control and use of water in the Gila River Basin, the problem was brought to the attention of the Sedimentation Subcommittee, Federal Interagency River Basin Committee. It was agreed among the agencies on that committee that a resurvey not only should be made, but should be extended to crest elevation (2523 feet) to correct once and for all the errors in valley slope topography. Agencies participating financially in the resurvey were the Corps of Engineers, Department of the Army; Bureau of Reclamation, Department of the Interior; Soil Conservation Service, Department of Agriculture; and the Gila Water Commissioner, Safford, Arizona.

Considerations of cost and time resulted in the decision to make a stereoprojection map with multiplex equipment from aerial photography and careful ground control. The Corps of Engineers, Los Angeles District, contracted the flight photography to Fairchild Aerial Surveys, Inc. The aerial photographs were made in October and November, 1946. Field engineering parties of the Corps of Engineers began ground control work in December 1946 and completed that phase of the work in May 1947. Horizontal control was established by triangulation and transit traverse throughout the reservoir area from network stations of the U. S. Coast

and Geodetic Survey and other agencies. Vertical control was established by level lines from the dam and other bench marks adjacent to the reservoir. In addition, a second order level line was run from San Carlos village to Coolidge Dam. Four new bench marks were established near and on the dam. Elevations of outlet gates and other key points were determined.

The pool area of some 1,400 acres below elevation 2,395, which could not be photographed for the stereoprojection map was sounded by a field party of the Soil Conservation Service between January 15 and 23, 1947. The original range ends or their extensions from the 1935 and 1937 surveys were located and flagged. Soundings, located by plane table intersection, were taken at frequent intervals, usually 25 feet apart but sometimes a few feet apart when abrupt changes in depth were encountered Water edge on each end of the range was mapped and elevation of water surface was determined each morning and afternoon from the water stage recorder operated by the U. S. Geological Survey at the dam. In addition to soundings on the ranges, a number of intermediate soundings were taken to allow better delineation of contours. Because of rise in water level since the flight date, sounding overlapped the stereoprojection map contour 2,390 on most ranges. Little inflow occurred during the survey; therefore, water surface elevation changed only slightly during the day. However, all soundings were corrected to prevailing water surface. A total of 18 ranges were sounded.

The aerial photographic survey and sounding survey were combined to produce a topographic map of the entire reservoir (figure 1).

From the sounding survey 5-foot contours from the lowest elevation, 2,370, to 2,395 feet were delineated. The stereoprojection map was made on a 10-foot contour interval above elevation 2,400 feet except on the valley floor where 5-foot contours were delineated. Because it was desirable to compute the capacity based on 5-foot contours for the entire reservoir, the contours mapped across the valley floor were interpolated for the entire reservoir basin as follows: All 10-foot contours were planimetered for the entire reservoir area. The 5-foot contours were drawn midway between the 10-foot contours from their disconnected ends on the valley flat to the edge of each map sheet and the 5-foot contour areas on that sheet were determined by planimetry. The mean of areas of the 10-foot contours above and below each 5-foot contour was determined for each additional sheet on which the 5-foot contour was not delineated. This area thus computed for each sheet was added to the planimetered area of the 5-foot contour to give the total area of the 5-foot contour for the reservoir.

Computation of the reservoir capacity as of January 1947 and for all earlier surveys was based on the formula:

$$V = \frac{h}{3}(A + \sqrt{AB} + B)$$

where: V = Volume between two successive contours
A = Area of lower contour
B = Area of upper contour
h = Contour interval

The surface area, capacity increments and cumulative capacity of all surveys up to elevation 2,530 feet, and including spillway crest at elevation 2,523 feet, is given by 5-foot contours in table 1. Figure 2 shows area and capacity curves as determined for the original and all three sediment surveys. From these data the Surface Water Division, U. S. Geological Survey, has prepared tables of the January 1947 capacity for each 0.1 foot from the lowest outlet gate at elevation 2,383 feet to elevation 2,529 feet.

The 1947 capacity of San Carlos Reservoir was shown by this survey to be 1,209,953 acre-feet at spillway elevation 2,523 feet. Usable capacity, which is limited by outlets at elevation 2382.63 feet, was 1,205,508 acre-feet. The sediment level at the dam was 13 feet below the outlets in 1947. The depth of sediment at that point was 62 feet.

Adjustment of original map and previous surveys. The 1947 capacity is less than the original capacity by the amount of sediment deposited since November 15, 1928. Comparison of the original capacity and capacities determined in 1935, 1937, and 1947 gives a measure not only of total sediment accumulation but also the rates over certain intervals of time. In addition, the changes in individual contours between surveys provide valuable data on sediment distribution. Furthermore, the intermediate surveys of 1935 and 1937 are useful in relating inflow and other hydrologic data to the probable long term rate of sediment accumulation, and expected variations from year to year.

Adjustment of previous surveys to the much more accurate 1947 survey was a complicated process because of various map scales, different standards of surveying, and incompleteness of mapping. As a first step, the original 1914-15 map and plane table sheets of the 1935 and 1937 surveys were adjusted by precise photographic enlargement or reduction based on common triangulation stations to the scale of the 1947 map. Since neither the 1935 nor 1937 surveys were extended to crest elevation, it was necessary to assume no change in valley slope topography above elevation 2,460 feet. This is probably a valid assumption because the average water level of San Carlos Reservoir stands far below that elevation and valley slopes are largely on erosion-resisting formations.

As the next step the contours for each earlier survey, where they crossed areas of sediment deposition or scour and hence differed from the 1947 contours, were transferred to a separate set of the 1947 maps. This resulted in an adjusted map for each previous survey, in which the correct slope topography of 1947 was combined with the topography of the earlier date that was subsequently altered by deposition or scour.

In a few places the topography of the 1935 and 1937 surveys on the sediment was slightly altered based on findings of the 1947 survey that, for example, small hills rising above the sediment level were missed in the earlier soundings.

It is believed that this procedure for adjustment resulted in the highest probable accuracy with which earlier contours could be reconstructed at a later date. All of the original 5-foot contours were transferred to the 1947 maps. The differences in area were planimetered for each contour and added to the 1947 contour area. Thus an adjusted original area table was developed. The same procedure was followed for the 1935 and 1937 surveys up through contours 2,475 and 2,460, respectively, which were the highest levels of mapping in those surveys. The composite 1935-1947 and 1937-1947 contours were replanimetered in their entirety up to elevations 2,475 and 2,460. Thus new 5-foot contour area tables were prepared for the original 1935 and 1937 surveys. From them, new capacity tables were computed by the formula given above. Differences represented the net sediment deposition between each survey. The data thus obtained are presented in table 1.

RESERVOIR SEDIMENTATION

Rates of sedimentation. From the beginning of impoundment, November 15, 1928, to January 22, 1947, a period of 18.19 years, 57,494 acre-feet of sediment accumulated in San Carlos Reservoir. The equivalent annual sedimentation rate was 3161 acre feet. The total loss of original storage capacity during this period was 4.54 percent, and the average annual rate of loss was 0.25 percent. These data and other results of the 1935, 1937, and 1947 surveys are shown in tables 3 and 4.

As discussed in a later section of this report, the measured rate of sedimentation is believed to be too low, mainly because the period of record was deficient in inflow as compared with the long-term period since 1896. Pre-construction estimates (7, 8) of the rate of sedimentation were considerably higher than those actually measured. From the data now available it is estimated that the long-term rate of sedimentation will average 5000 acre feet.

Comparison of rates of sedimentation between successive surveys, as shown in tables 3 and 4, does not reveal any effects of the inflow of 1941, the highest during the period of sedimentation. Because of the extremely low flow of several other years between 1937 and 1947, however, it may be that any effects of the large 1941 inflow have been counterbalanced. On the other hand, several other factors may have contributed to decline of the sedimentation rate since 1937. Among the possible contributing factors are the following:

(1) Spread of salt cedars and other riparian vegetation on the floodplains and in the channels upstream, a condition that tends to hold back sediment in the channels and on the floodplains, especially in the absence of large flushing flood flows.

Table 1 - SURFACE AREA, CAPACITY INCREMENTS, AND CUMULATIVE CAPACITY OF ORIGINAL AND ALL SURVEYS BY 5-FOOT CONTOUR INTERVALS.

CONTOUR Feet abv. mean sea level	1915 CAPACITY (ADJUSTED) (Used for 1928)			1935 SURVEY (ADJUSTED)			1937 CAPACITY (ADJUSTED)			1947 SURVEY		
	Area	Capacity to next lower contour	Cumulative capacity	Area	Capacity to next lower contour	Cumulative capacity	Area	Capacity to next lower contour	Cumulative capacity	Area	Capacity to next lower contour	Cumulative capacity
	acres	ac.ft.	ac.ft.	acres	ac.ft.	ac.ft.	acres	ac.ft.	ac.ft.	acres	ac.ft.	ac.ft.
2308	Original bottom at dam		0	0	0	0	Original bottom at dam					
2365	489	6,060	6,060	66	5	5	55	4	4	0	0	0
70	830	3,307	9,367	428	1,103	1,108	363	932	936	6	1	1
75	1,116	4,956	14,323	768	2,949	4,057	622	2,434	3,370	227	450	450
80	1,511	6,523	20,846	1,127	4,709	8,766	1,021	4,069	7,439	524	1,827	2,277
85	1,825	8,162	29,008	1,362	6,213	14,979	1,284	5,704	13,143	803	3,293	5,570
90	2,048	9,396	38,404	1,624	7,456	22,435	1,570	7,071	20,215	1,182	4,932	10,502
95	2,309	10,626	49,030	1,824	8,615	31,050	1,835	8,504	28,719	1,454	6,578	17,080
2400	2,681	12,347	61,377	2,253	10,174	41,224	2,214	10,108	38,827	2,083	8,796	25,876
05	3,079	14,522	75,899	2,651	12,247	53,471	2,717	12,306	51,133	2,493	11,425	37,301
10	3,397	16,434	92,333	3,020	14,168	67,639	3,067	14,451	65,584	2,902	13,475	50,776
15	3,706	18,315	110,648	3,481	16,239	83,878	3,430	16,234	81,819	3,315	15,531	66,307
20	4,152	20,559	131,207	3,922	18,497	102,375	3,797	18,060	99,879	3,741	17,630	83,937
25	4,612	23,984	155,191	4,537	21,129	123,504	4,455	20,609	120,487	4,391	20,309	104,246
30	-- 1/	25,547	180,738	5,197	24,317	147,821	5,084	23,831	144,318	5,099	23,703	127,949
35	--	28,303	209,041	5,649	27,108	174,929	5,648	26,818	171,136	5,564	26,650	154,599
2/40	6,250	29,735 2/	238,776	6,250	29,735	204,664	6,296	29,846	200,982	6,143	29,256	183,853
45	6,845	32,727	271,503	6,845	32,727	237,391	6,896	32,969	233,951	6,731	32,174	216,029
50	7,467	35,769	307,272	7,467	35,769	273,160	7,531	36,057	270,008	7,381	35,268	251,297
55	8,060	38,809	346,081	8,060	38,809	311,969	8,145	39,180	309,188	7,971	38,371	289,669
60	8,841	42,238	388,319	8,841	42,238	354,207	8,884	42,560	351,748	8,900	42,157	331,826
65	9,778	46,529	434,848	9,778	46,529	400,736	9,808	46,712	398,460	9,617	46,282	378,108
70	10,501	50,688	485,536	10,501	50,688	451,424	10,516	50,801	449,261	10,522	50,332	428,439
75	11,187	54,212	539,748	11,187	54,212	505,636	11,183	54,238	503,498	11,133	54,131	482,570
80	11,887	57,677	597,425	11,887	57,677	563,313	11,905	57,709	561,207	11,832	57,405	539,975
85	12,682	61,413	658,838	12,682	61,413	624,726	12,685	61,466	622,673	12,689	61,291	601,266
90	13,516	65,485	724,323	13,516	65,485	690,212	13,519	65,500	688,174	13,528	65,533	666,799
95	14,320	69,582	793,905	14,320	69,582	759,793	14,320	69,589	757,763	14,320	69,612	736,411
3/2500	15,250	73,914	867,819	15,250	73,914	833,708	15,250	73,914	831,677	15,250	73,914	810,325
05	16,116	78,407	946,226	16,116	78,407	912,114	16,116	78,407	910,084	16,116	78,407	888,732
10	17,027	82,849	1,029,075	17,027	82,849	994,963	17,027	82,849	992,933	17,027	82,849	971,581
15	17,991	87,536	1,116,611	17,991	87,536	1,082,499	17,991	87,536	1,080,468	17,991	87,536	1,059,116
20	18,974	92,403	1,209,014	18,974	92,403	1,174,902	18,974	92,403	1,172,872	18,974	92,403	1,151,520
Spill crest 2523	19,581	58,433	1,267,447	19,581	58,433	1,233,335	19,581	58,433	1,231,305	19,581	58,433	1,209,953
25		38,956	1,306,403	19,985	38,956	1,272,291	19,985	38,956	1,270,260	19,985	38,956	1,248,908
30		102,677	1,409,080	21,090	102,677	1,374,968	21,090	102,677	1,372,937	21,090	102,677	1,351,586

1/ Area of these contours is interpolated on the plotted curves by joining adjacent points of contour 2425 and 2440.

2/ No change in area-capacity above 2440 feet elevation, 1915-35.

3/ No change in area and capacity since 1915 above 2500 feet elevation.

(2) Construction of debris barriers, terraces, and other types of sediment control structures, mainly by the Civilian Conservation Corps prior to the 1941 flood. Although many of these structures are no longer functioning for lack of maintenance or due to filling of their debris capacity, there is considerable evidence of their effectiveness from 1937 to 1941 or later.

(3) Land leveling on irrigated floodplain and bench lands since 1941 has tended to reduce runoff and return flow over the land surface and hence has reduced soil erosion and the amount of sediment reaching the main streams from irrigated land.

(4) An estimated 1200 acre feet of sediment is now diverted annually, on the average, in irrigation water. This represents most of the sediment carried during dry years because nearly all of the stream flow is diverted. Because of less return flow over the surface and land leveling, a larger percentage of this sediment has been deposited on irrigated land.

(5) A small amount of sediment may have been flushed through outlet works in the dam. Very low reservoir stages at the time of sediment laden inflows are conducive to venting of density currents and to erosion of deposits adjacent to outlets.

(6) Exposure of deposits during prolonged low reservoir stages since 1941 undoubtedly resulted in considerable compaction of sediment deposited in earlier years. The decreased volume of earlier deposits would cause an apparent decrease in the rate of accumulation for the period 1937-47.

Higher inflow, eradication of riparian vegetation, and deterioration of watershed conditions are factors that would tend to again increase the average rate of sedimentation.

Distribution of Sediment. All sediment entering San Carlos Reservoir has been deposited well below crest elevation 2,523 and most of it below elevation 2,460 feet. The highest reservoir stage of record in March 1942 was 2,502 feet. The lowest and thickest sediments are silt and clay bottomset beds which are confined mainly to the old stream bed in the canyon section extending from the dam to approximately four miles upstream. The sediment beds extend beyond the old channel in places over benches and into former tributary canyons which are now submerged. These beds are normally under water but large areas have been exposed to drying for long periods in recent years. At the dam the deposits are 62 feet thick. Progressively upstream they thin out at a rather uniform rate for several miles. The top of the sediment is relatively flat from bank to bank and very gently sloping toward the dam. Bottomset beds comprise about two-thirds of the total sediment volume.

Approximately three miles above the dam is the beginning of the present delta deposits. These overlie the upper end of the bottomset deposits and represent the upstream edge of the normal winter water level in the reservoir. The deltaic deposits are a composite feature, representing deposition at various water levels and scour channel erosion when the delta is exposed at low water. Delta deposits are found for several miles above their downstream edge. In general they start at about elevation 2,390 feet and lie on the lake floor to about bottom elevation 2,460. These deposits are exposed to air drying most of the time because San Carlos is usually drawn down every summer in the process of releasing water for irrigation. Delta beds are heterogeneous mixtures of sand and silt, often interbedded with clay or silt layers.

In addition to delta deposits of the Gila River a considerable number of small deltas have formed at the mouths of sidewashes and small tributaries. These sediments are typically sandy, gravelly, and poorly bedded. In places they overlay or are interbedded with bottomset beds or delta deposits. Other fans are deposited above prevailing water levels on the pre-reservoir terraces. Older water levels have produced eroded gravel benches cut by wave action and bordered by washed gravel ledges. These stand 25 to 100 feet above the normal water level and make a conspicuous fringe around most of the reservoir basin.

Most of the upper reservoir basin, especially the delta deposits, are covered by a dense growth of salt cedar. Its density and distribution was apparently increased by the 1941 flood when the reservoir had its maximum water level to date. At present, these vegetated areas are trapping sediment, both from the Gila River and side wash flows. Frequent meandering and scour has produced complex deposits that are unsorted, heterogeneous, usually unbedded. Their thickness is highly variable from place to place.

Figure 3 shows clearly that most of the sediment is deposited in the lower end of the reservoir. The dead storage pool is nearly full. One-fourth of the total sediment is deposited in the lowest 31 percent of the depth. One-half is deposited in the lowest 39 percent, and three-fourths in the lowest 49 percent. Figure 3 also shows on the left-hand scale the distribution in terms of percent of distance from the dam as measured along the principal axis of San Carlos Reservoir. Nearly all of the sediment is deposited within 45 percent, or 10 miles of the dam. The surveys of 1935 and 1937, although not plotted because of incompleteness of mapping, showed all deposits to be lower than in 1947. Therefore the mean locus of sediment deposition is moving progressively up the reservoir basin.

Character of sediment. The sediment accumulated in San Carlos Reservoir ranges from clay in the lower reaches to gravel and cobble found in tributary fans. Deposits lying against the dam consist predominantly of colloidal clay. Progressively up-lake the sediment grades into silty clay and near the delta becomes mainly silt and very fine sand. Delta deposits show considerable variety of texture; they are

principally silty in mid-lake and grading to fine sand laterally. Occasionally tongues of medium sand with some gravel brought in by a side wash are deposited on fine sands and silts in the delta. Reworking by wind action of exposed and dried delta surfaces often forms miniature dunes and long ridges of fine sand, especially where vegetation has started. These wind-blown sediments later become inundated and acquire a thin crust of silty deposits. On re-exposure they develop mud-cracked surfaces. Extreme drawdowns cause eroded silts and fine sands from the delta to be transported within a mile of the dam. These are interspersed with the clays and although quantitatively small they add grittiness to a normally soft, palpable sediment.

Although no samples were taken to determine specific weight, it is believed to be similar to or perhaps slightly higher than that of other reservoirs of the Southwest. The dry weight of fine sediment per unit volume increases materially with time during the life of a reservoir as a result of compaction from water loss, chemical changes, overburden of additional deposits, and perhaps other causes. The maximum weight is attained more rapidly when lake deposited sediment is exposed to drying at frequent intervals and for long periods as in San Carlos Reservoir.

The range in specific weight is also influenced by the kind of sediment. Thus lower values can be expected if clays and silts predominate and are continuously inundated than if sands and gravels comprise the bulk of sediment. Because San Carlos sediments tend to be sandy and even the finest sediment has been subjected to considerable exposure and desiccation, the mean specific weight is considered to be relatively high. A review of studies and reports on sediments made of other reservoirs having similar characteristics indicates that the maximum specific weight which might be attained is between 70 and 90 pounds per cubic foot. The average specific weight of San Carlos sediment at the time of the 1947 survey is estimated to be approximately 70 pounds per cubic foot.

CHARACTER OF DRAINAGE AREA

Boundaries and area. The Upper Gila River drainage area above Coolidge Dam contains approximately 12,900 square miles of which 7,300 square miles is in southeastern Arizona and 5,600 square miles is in southwestern New Mexico. For approximately 120 miles the eastern boundary of the watershed forms the Continental Divide in New Mexico and separates the Gila from the Rio Grande drainage lying to the eastward. The northern boundary separates the Gila drainage from the Salt River drainage and from a large closed basin in New Mexico. The southern boundary separates the Upper Gila from the San Pedro, which is another large Gila tributary entering below San Carlos Reservoir.

Physiography. The Upper Gila drainage lies in the Mexican highland section of the Basin and Range physiographic province. This section

consists of rugged mountainous areas separated by valley plains. The mountain altitudes range from approximately 5,000 feet to more than 11,000 feet. The entire drainage area is ringed, clockwise from Coolidge Dam, by the following ranges: Pinal, Blue, Gallo, Tularosa, Mogollon, Black, Peloncillo, Chiricahua, Dos Cabezas, and Pinaleno. The Gila River cuts through the ring on the west side in a rocky gorge which provides the site for Coolidge Dam. From here at a river-bed elevation of 2,308 feet, the main stem valley, known as the Safford Valley, rises to the eastward for about 70 miles before it intersects the mountain sections at about 3,500 feet elevation. In this reach the valley width varies from about 10 to 20 miles. However, an inner valley about 5 miles wide is entrenched within the valley floor. This contains the principal farm lands and the river channel. Eastward and beyond the Safford Valley are smaller and narrower valley reaches at higher elevations, separated by low mountains running transversely north and south. Although physiographically connected to the Safford Valley, these are named progressively upstream the Duncan, Virden, Red Rock, and Cliff-Gila Valleys. San Simon Creek, the largest southern tributary to the Upper Gila, lies in a fairly straight valley approximately 100 miles long by 20 miles wide. It joins the Safford Valley near its eastern end at Solomonsville. Other tributaries, such as Bonita and Eagle Creeks, have small and narrow floodplains in their lower reaches. In most respects these smaller valleys are miniatures of the main stem valley. In common with most southwestern streams, the Upper Gila valleys have relatively steep gradients.

Stream system. The Upper Gila River rises in the high plateau country of southwestern New Mexico and flows south and west about 250 miles before it enters San Carlos Reservoir. In mountainous areas the channel gradient ranges from 50 to 300 feet per mile. In the lower reaches gradients are from 7 to 13 feet per mile. The lower reach is entrenched in valley alluvium and shows at least two cycles of geological erosion. The upper reaches are geologically incised into canyons of the surrounding mountains. Flood plains are absent, or poorly developed in narrow bands bordering the channels. Principal tributaries entering from the north are San Francisco and San Carlos Rivers, and Eagle and Bonita Creeks; from the south, San Simon Creek. The major tributary, San Francisco River, and its tributary, the Blue River, contribute the largest quantity of water but a relatively low proportion of the sediment. Numerous smaller tributaries enter the Gila River, principally in the upstream mountainous areas. More than a hundred "dry" washes having draining areas ranging in size from 5 to 190 square miles join the main stem directly. These are found mostly along the middle and lower reaches. The washes carry no water most of the time, but they are capable of large and destructive flood flows of short duration when storms of high intensity occur over their watersheds. Some areas lying within the basin are noncontributing most or all of the time. These include closed basins which are structurally cut off, basins which have been isolated by deposition of sediment at the lower end, and semiclosed basins which receive insufficient runoff to reach connected channels of the main stem system except during years of unusually

high precipitation. The total area which is considered closed or semiclosed is difficult to ascertain from existing maps but is estimated to be 1,000 square miles.

Geology and structure. The mountain masses which form the watershed boundary are principally crystalline intrusives, metamorphics, and volcanic flows, but include a few old sedimentary formations. Ranges along the south and east boundaries are predominantly granite, gneiss, and schists of pre-Cambrian age. In places these rocks are faulted and intruded by quartz-monzonite porphyry, diorite, and granite of Mesozoic age. The western boundary is formed partly by steeply dipping early Paleozoic quartzites, marbles, limestones, and schists. These are the rocks on which Coolidge Dam is built. A succession of flows, aggregating several thousand feet, of rhyolite, andesite, or basalt with interbedded tuffs, breccias, and agglomerates make up the Peloncillo, Chiricahua, Dos Cabezas, Mogollon, and Black Ranges. In places these volcanics are interbedded with sandstones. Numerous faults and fractures penetrate the mountain ranges. Nearly half of the watershed area consists of volcanic rocks. Local folding occurs but generally the volcanics and associated rocks are nearly horizontal or slightly tilted to the east or northeast.

The valley in which the Gila River flows is a series of troughs arranged in step-like pattern and separated by low hills trending north-south. These troughs are deeply filled by gravels, sands, silts, and clays. Their early history probably involves downcutting of the ancestral Gila River as the land surface rose. In Tertiary time the stream was obstructed by faulting and by lava dams. Lakes were formed which received extensive deposits from adjacent mountains. Possibly 2,000 feet of detrital material, volcanic ash, and precipitates were accumulated before the outflow from these lakes cut through their natural barriers, thus draining them. Today these old lake beds form extensive high terraces and bluffs on both sides of the valley. Drainages from the high mountains into the old lakes produced large fans of gravel and sand. These are found now as thick fanglomerates at the edge of the valley. The inner valley is a former flood plain that is now trenched by the modern stream. Pediment slopes and talus lie at the valley edge in places. In addition to lake deposits, the San Simon Valley contains a considerable body of windblown material.

Climate and rainfall. The wide range in altitude from 2,300 to 11,000 feet is reflected in an equally wide range of climatic conditions. Precipitation in the Safford and San Simon Valleys averages about 8 inches annually. In the highest mountain areas the average is about 35 inches. Precipitation occurs principally as snow in higher elevations and as rain elsewhere. Two distinct storm seasons occur: June to September and November to March. The relative humidity is low and the climate is characteristically dry. Temperatures in summer are high in the valley; moderate in the mountains. Daily temperatures exceeding 100 degrees are common in summer below 3,500 feet elevation.

In winter, temperature seldom falls below 20 degrees in this same zone, but in the higher mountains, a temperature of -30 degrees has been recorded. Normally the Safford Valley has about 200 frost-free days annually.

Vegetation. Native plant cover is sparse in the valleys, being represented mainly by desert shrubs. These include creosote bush, mesquite, cactus, and annuals, interspersed in periods of favorable precipitation with annuals and weeds. Grass is scarce in most places but toboza, grama, and mesquite grass occur in the more favorable sites. Foothill and lower mountain areas receiving more rainfall have juniper, oak, and some pinon. More grass and annuals are present. In the mountain areas, which have considerably more rainfall, a forest stand of pines, firs, and other trees develops where soil exists. Grass is rather plentiful in the mountain areas except where overgrazed by livestock. Along the channels grow baccharis, willows, cottonwood, and lately in the valley sections a heavy infestation of salt cedar.

Soils and erosion. In comparison with most of the United States, true soils are undeveloped or absent over large areas of the Upper Gila drainage area. Deep alluvial soils, comprising only 3 percent of the watershed, are confined to first bottom lands, low terraces, and fans of the valley. These soils are used principally for farming and in places are being eroded rapidly. Other deep soils occur in the San Simon Valley on old valley fill, lake beds, and fan deposits. These are less suitable for cultivation because of contained salts, and lack of suitable or adequate water supply. In general, the deep soils are sandy to moderately heavy, are easily eroded, and have a scant or no vegetative cover. Soils of moderate depth are widely distributed in the foothills, mountains, and rolling land. They develop variously on old valley fill, igneous, and sometimes on sedimentary rock. Sheet and gully erosion is prevalent at lower elevations. Considerable grazing by sheep and cattle occurs on this soil type.

Shallow soils occur throughout the mountainous and hilly area. The texture ranges from medium to moderately heavy. They were developed on all rock types but particularly on igneous and metamorphic rocks. About one-tenth of the area mapped by the Soil Conservation Service as shallow soil is actually bare rock.

Erosion is widespread but sediment production is low because of shallow depth available to destruction. Much of the present erosion can be traced to man's activities in ranching, farming, lumber and mining operations, road building, and other processes. Erosion which appears to be of geological origin is occurring, however, in places such as old lakebed terraces and in the higher elevations. In preparing a flood control survey report of the U. S. Department of Agriculture on the Upper Gila River watershed, a study was made by the Soil Conservation Service of erosion and sedimentation, especially as it concerned San Carlos Reservoir. Evaluations of bank cutting, fill behind debris barriers, gully cutting, and soil losses from sheet erosion were

related to geology, soil types, slopes, and land use. These studies, together with comparison of fragmentary suspended load measurements on the Upper Gila and its principal tributaries gave a basis for estimating the relative sediment contributions from each tributary and the area it drained. The results are shown in figure 4.

Land ownership and use. Public lands occupy 86 percent of the watershed. Of these, 71 percent are Federally-owned or administered. This area may be further broken down as follows:

National Forest	35 percent
Federal Range	21 percent
Indian Lands	14 percent
Other Federal	1 percent
	71 percent

State lands comprise 15 percent and privately owned land makes up the remaining 14 percent.

According to usage, the land may be classified as follows:

Grazing	83.0 percent
Timber and forest products	16.0 percent
Farming	.7 percent
Other	.3 percent
	100.0 percent

Some multiple use is made of timber lands for grazing and recreation. The principal livestock production is cattle and sheep. Farm products include cotton, small grains, fruit, nuts, and vegetables. Nearly all of the farmed land is irrigated. Timber products include saw timber, ties, and firewood.

Other land uses in the watershed include recreation, mining, urban, highway and railroad, Indian reservations, and reservoirs.

Soil conservation. In 1934 the Soil Erosion Service, which became the Soil Conservation Service in 1935, began erosion control demonstrations in the Gila River watershed, mainly in the Safford and Duncan Valleys, with labor supplied by the Civilian Conservation Corps from several camps established nearby. Over a 6-year period a large number of spreaders, bank protection structures, and sediment barriers were built, and a variety of land treatment practices were tried. Some of the measures were admittedly experimental and were installed as field trials. As might be expected, because of lack of precedence for watershed protection of this scope some of these measures were failures. Many, however, were successful. The local landowners were interested spectators and undoubtedly these trial measures did much to promote landowner interest in conservation.

Since 1940 landowners in the watershed have become increasingly interested in applying soil and water conservation practices largely at their own expense. This is especially true of farmers on irrigated land. As a result, about 25 percent of the irrigated farm acreage has been treated, mainly by leveling. Eight locally organized and managed soil conservation districts are now functioning within the watershed. All of them are receiving technical assistance from the Soil Conservation Service.

Several reasons are apparent for the present landowner interest in conservation. Perhaps the first and most impelling has been the insufficiency of water for irrigation and the consequent need for improved efficiency in the use of irrigation water supply. Another major reason was the observed widespread destruction of some of the best valley land by erosion. Despite the magnitude of the conservation job, the existence now of adequate local organization for cooperation, such as exists in the soil conservation districts, indicates that needed treatment of irrigated lands may be completed within a relatively few years.

Interest in range land management has not kept pace with the irrigation farmers' interests, but even in this field there are encouraging signs. Range improvement, however, is inherently far more difficult and slow.

The Production and Marketing Administration has aided financially in conservation work on Indian lands as well as by payments to private landowners and operators for conservation practices.

The Forest Service has carried on range improvement, road work, and erosion control within the national forests of the watershed. Fire control and maintenance of recreational areas are also conservation practices of the Forest Service.

The Bureau of Land Management, Department of the Interior, has aided in adjusting grazing use of range lands, and improvement of vegetative cover on public lands has been made through exclusion and building of minor structures.

The Office of Indian Affairs, Department of the Interior, has done reseeding, water spreading, and bank erosion control within the San Carlos Reservation.

Special studies of water consumption by salt cedars (tamarisk) and other bottom land vegetation have been made in the Safford Valley by the Surface Water Division, U. S. Geological Survey (5, 12). The invasion by salt cedars is a comparatively recent development but their presence causes a number of serious problems connected with water loss, sediment deposition, and creation of flood hazards. Several government and private agencies are attempting to learn how salt cedars can be eradicated economically.

INFLOW AND WATER USE

The average annual stream flow of the Gila River into or at the site of San Carlos Reservoir, as measured between 1896 and 1947, was 346,712 acre-feet. The U. S. Geological Survey (16) has maintained stream gauges at the following sites for the periods indicated:

Gila River near Coolidge Dam Site	(July 1899 - Nov. 1905	8 miles above Coolidge Dam
	(Aug. 1910 - Feb. 1911	9 miles above Coolidge Dam
	(Apr. 1914 - Oct. 1928	600 feet below Coolidge Dam
	(Oct. 1928 - Present	At Coolidge Dam
Gila River at Calva	March 1929 - Present	At head of reservoir
San Carlos River	(Aug. 1910 - Jan. 1911	Near Peridot
	(Apr. 1914 - Sept. 1915	" "
	(Mar. 1929 - Present	" "

Older records of stream flow were obtained above and below Coolidge Dam. Fragmentary records exist back to 1865, but generally they are of doubtful value prior to 1895.

From these records the flow has been computed and adjusted for losses in bank storage, channels, and evaporation. Upstream gauges are also maintained at several sites. These have been established at various dates, and their records are useful in determining effects of tributary inflows, channel losses, measurement of diverted and added flows from return and pump irrigation waters. Wide variation in flows and in seasonal distribution are normal for Southwestern streams. Figure 5 shows annual variations in the flow at San Carlos site since 1896, and it reflects the wide fluctuations which have been found at all upstream gauges.

Water yield comes mainly from the higher elevations of the watershed. The estimated average annual yield per square mile is 55 acre-feet from the San Francisco River, 47 acre-feet from the Upper Gila above Red Rock, and 38 acre-feet from the San Carlos River. By contrast the San Simon River, which drains one-fifth of the total Upper Gila drainage area but at much lower elevations, yields only 4 acre-feet of water per square mile. This is probably about the same as yields from the Safford Valley.

Approximately three-fourths of the runoff can be expected between October and May. Flood control studies by the Soil Conservation Service (13) indicate that nearly 30 percent of the total water yield comes in flood flows. Runoff between June and September is caused almost entirely by high intensity thunderstorms. These are responsible for the flash floods and relatively high erosion in the lower watershed.

The principal water use in the drainage area is for irrigation. Other uses include urban and domestic, mining, stock water, and nonbeneficial consumption by salt cedars and other riparian vegetation. In dry years virtually all stream flow above San Carlos Reservoir is diverted to irrigation, and only return flow, ground water accretion, and flash flood flows are received by San Carlos Reservoir. In dry years the stream flow is inadequate and ground water pumping is necessary to augment the supply.

Records of diversions are kept by the Gila Water Commissioner (6). The U. S. Geological Survey, Ground-water Division, records pumping data. From these sources the comparative data on diversions, pumping, and stream flow for eight years are given in table 2.

Table 2 - GROUND WATER PUMPING AND STREAM FLOW INTO AND FROM SAFFORD VALLEY

Calendar Year	Diversion	Pumping	Stream Flow	
			Gila-Solomonsville 1/	Calva 2/
	ac. ft.	ac. ft.	ac. ft.	ac. ft.
1940	99,693	24,600	302,600	220,310
1941	151,300	8,685	917,770	900,380
1942	172,005	18,900	221,560	314,300
1943	121,569	35,000	150,700	93,180
1944	128,027	52,000	151,290	96,555
1945	148,675	35,200	219,700	118,407
1946	69,909	115,000	116,234	54,381
1947	51,978	100,000	100,120	39,050

1/ Gila near Solomonville gauge measures flow at head of Safford Valley

2/ Calva gauge is located at head of San Carlos Reservoir and measures flow out of Safford Valley.

Data from the Safford Valley is given because it contains most of the irrigated land and uses proportionally most of the water. However, increase in pumping is shown in nearly all irrigated districts. From table 2 it is obvious that during periods of low runoff stream flow alone is insufficient for existing irrigated acreage.

RELATION OF INFLOW TO SEDIMENTATION

As San Carlos Reservoir has never spilled and the loss of sediment by releases is negligible, the deposits within the reservoir represent virtually all of the sediment carried by the Gila River between November 15, 1928, and January 22, 1947, a period of 18.19 years. Table 3 shows how much water carried this sediment during each period of accumulation. It is significant to note not only that the rate of accumulation has declined but also that the average sediment concentration in the flow has decreased. The average annual inflow for the 18.19-year period is 255,118 acre-feet. This is 73.6 percent of the 52-year average. Figure 5 shows the annual flow for each year since 1896 as well as superimposed curves of average inflow to each year from the beginning of the long term record and from the beginning of storage in San Carlos Reservoir.

Reason for the decline in runoff can be ascribed principally to smaller precipitation during the period of San Carlos storage. Long dry periods in the Southwest are not unusual but it is not possible at present to predict accurately their duration or intensity. In addition to lesser precipitation, a decline in water flow can be charged partly to recent widespread growth of salt cedars, especially since 1935. The U. S. Geological Survey, Surface Water Branch (12), has estimated that nonbeneficial vegetation consumes 28,000 acre-feet annually in the Safford Valley alone. This is probably a minimum estimate because it was made on 9,300 acres and at least 13,000 acres of salt cedar are now present in the Safford Valley. Although no accurate data are available, it is also known that water consumption by urban, industrial, and mining has increased appreciably in recent years.

The inflow and sedimentation during periods covered by the 1935, 1937, and 1947 surveys are shown in table 3.

Table 3 - WATER INFLOW AND SEDIMENT CONTENT BETWEEN SURVEYS AND FROM BEGINNING OF STORAGE

Interval	Years	Pct. of Time	Water Inflow			Sediment		
			Amount	Pct. of Total	Av. annual	Period	Av. annual	Concentration
	no.	pct.	ac.ft.	pct.	ac.ft.	ac.ft.	ac.ft.	pct.*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Nov. 15, 1928 Feb. 25, 1935	6.28	34.5	1,752,610	37.8	279,078	34,112	5,432	1.95
Feb. 25, 1935 Jan. 22, 1937	1.91	10.5	343,210	7.4	179,691	2,030	1,063	.59
Nov. 15, 1928 Jan. 22, 1937	8.19	45.02	2,095,820	45.2	255,900	36,142	4,413	1.72
Jan. 22, 1937 Jan. 22, 1947	10.00	54.98	2,544,770	54.8	254,477	21,352	2,135	.84
Nov. 15, 1928 Jan. 22, 1947	18.19	100.0	4,640,590	100.0	255,118	57,494	3,161	1.24

* Percent of sediment by volume (Column 7 ÷ Column 4)

Decline in inflow and effects of releases are clearly shown by water surface elevation, which has been recorded daily since storage began. In recent years the water surface has been lowered to the bottom of the outlet gates several times. When this happens, especially early in the summer, a severe shortage occurs in the irrigated districts below the reservoir. Figure 6 shows surface water levels recorded in San Carlos since 1928.

CONCLUSIONS

If the measured average annual sediment concentration by volume in inflow of 1.24 percent for the 18.19-year period of record were applied to the 346,712 acre-feet average flow for 52 years, the expected long term rate of sediment accumulation would be 4,296 acre-feet. Other studies as on the Colorado (3) and the Missouri (11) Rivers show, however, that sediment may increase by some exponential factor with increase in runoff. It would appear, therefore, that an annual sedimentation rate of at least 5,000 acre-feet per year is possible and even probable if future runoff and watershed conditions approximate those of the long-term period since 1896.

Although the period since 1937 has been abnormally deficient in runoff and sediment production, some of the later changes such as increased diversion of sediment into irrigation systems, greater consumption of water by municipal, industrial, other activities, and vegetative growth in the valley may prevent the inflow of sediment into San Carlos from reaching its earlier magnitude. Considering all factors, however, it would appear prudent to use for future estimation an average sediment rate of 5,000 acre-feet per year. It is believed that this value would include a sufficient safety factor to preclude serious miscalculation of the future life and efficiency of operation of the reservoir.

At 5,000 acre-feet per year, the annual sediment contribution of the sediment-contributing drainage area (11,900 sq. mi.) would be .42 acre-feet per square mile.

The large initial capacity of San Carlos Reservoir insures a relatively long life for irrigation storage. If a future average annual sedimentation rate of 5000 acre-feet is estimated, an additional 112 years will have elapsed (from 1947) before the reservoir capacity is depleted 50 percent. However, evaporation and spillway losses will become larger as the surface area increases and the capacity decreases with sediment deposition, so that the service value of the reservoir will begin to decline before that date.

Although primarily an irrigation storage reservoir, San Carlos provides incidental flood protection to several downstream cities to the extent that storage above the pre-flood water level is available in reducing flood volumes and flood peaks. In future years, the incidental control of floods will diminish as the reservoir storage is depleted by sedimentation. San Carlos Reservoir also has considerable value as a sediment retention basin in preventing damages to channels and irrigated lands downstream. Gradually as capacity is lost, the amount of sediment carried through the outlets and over the spillway may be expected to increase and downstream protection to decrease. Estimation of the rate of change in trap efficiency is complicated by lack of information on how much sediment will deposit above crest and the degree of compaction or shrinkage with time. It appears likely, however, that San Carlos will be a highly effective sediment trap for at least another hundred years. These conclusions are also based on the assumption that watershed conditions will not change in the future. The construction of upstream reservoirs, soil conservation measures, and possibly other factors might change both the runoff regime and sediment inflow to the reservoir.

Table 4 - SUMMARY OF PERTINENT DATA
SAN CARLOS RESERVOIR, ARIZONA

		Unit	1935 Survey	1937 Survey	1947 Survey
Age 1/		years	6.28	8.19	18.19
Watershed area		sq. mi.		12,900	
Estimated sediment-contributing area		sq. mi.		11,900	
Reservoir					
Area at crest stage	original, & when surveyed	acres		19,581	
Storage capacity	original at elevation 2523	ac. ft.		1,267,447	
	at time of survey	ac. ft.	1,233,335	1,231,305	1,209,953
Capacity per sq. mil. of drainage area 2/	original	ac. ft.		98.25	
	at date of survey	ac. ft.	95.61	95.45	93.79
Sedimentation					
Total deposits below crest		ac. ft.	34,112	36,142	57,494
Average annual accumulation		ac. ft.	5,432	4,413	3,161
Annual accumulation per 100 sq. mi.		ac. ft.	42.1	34.2	24.5
Annual accumulation per acre (volume)		cu. ft.	28.65	23.28	16.68
Annual accumulation per acre (weight 3/)		tons	1.00	.81	.58
Depletion of storage					
Loss, original capacity per year		percent	.43	.35	.25
Loss, original capacity to date of survey		percent	2.69	2.85	4.54

1/ Storage began November 15, 1928. Average dates of survey: Feb. 25, 1935; Jan. 22, 1937; Jan. 22, 1947
2/ Including area of reservoir
3/ Estimated 70 pounds per cubic foot

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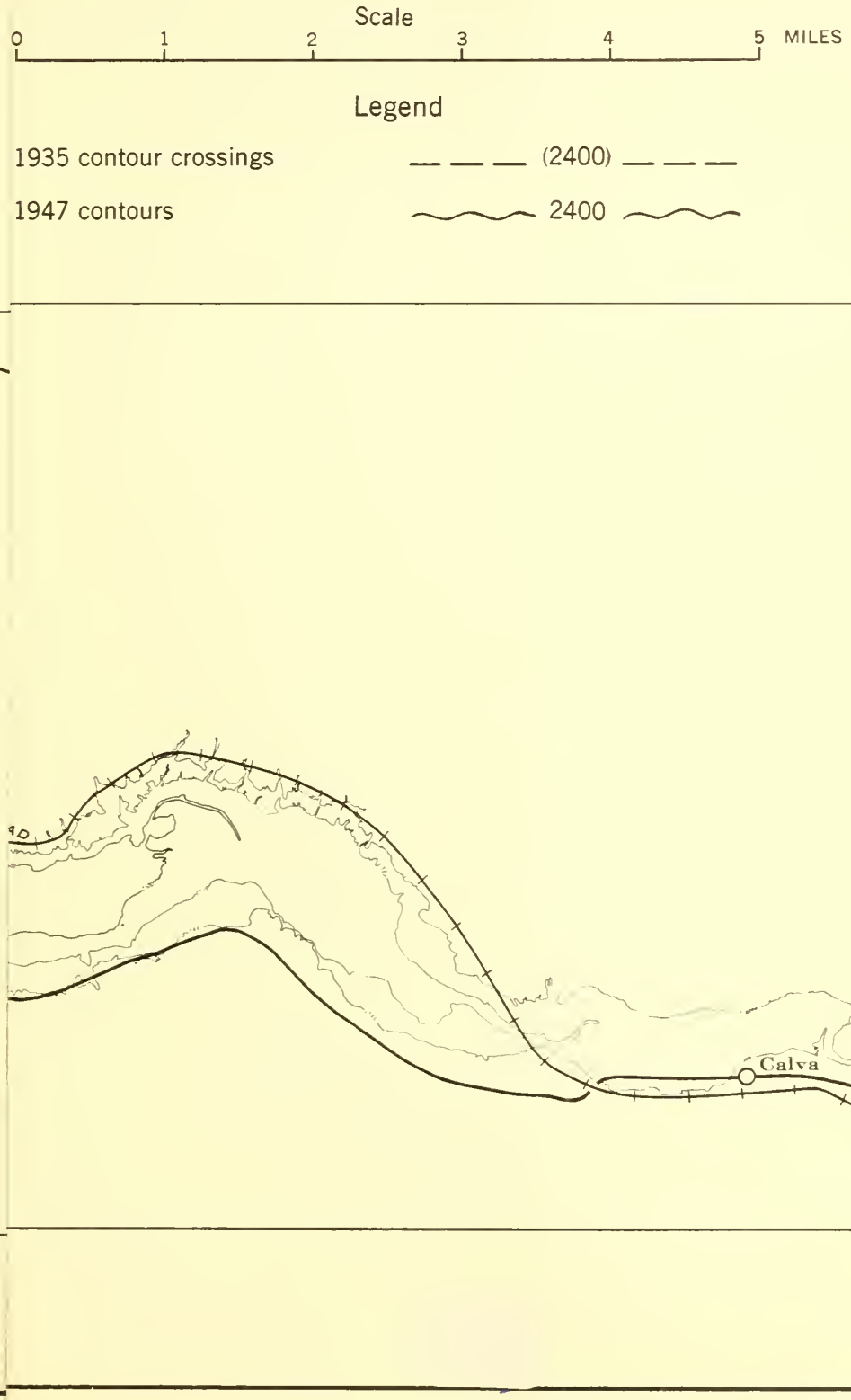
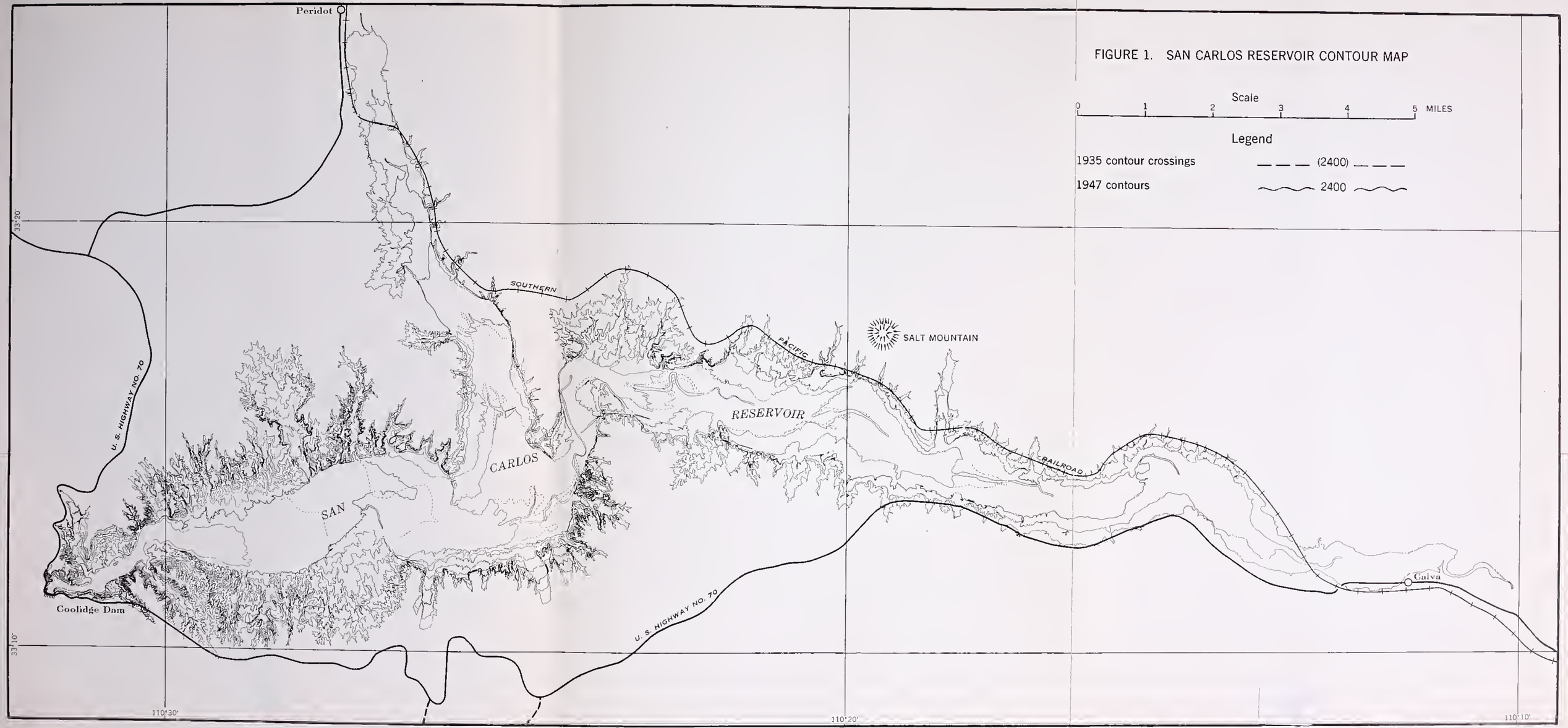
FIGURE 1. SAN CARLOS RESERVOIR CONTOUR MAP





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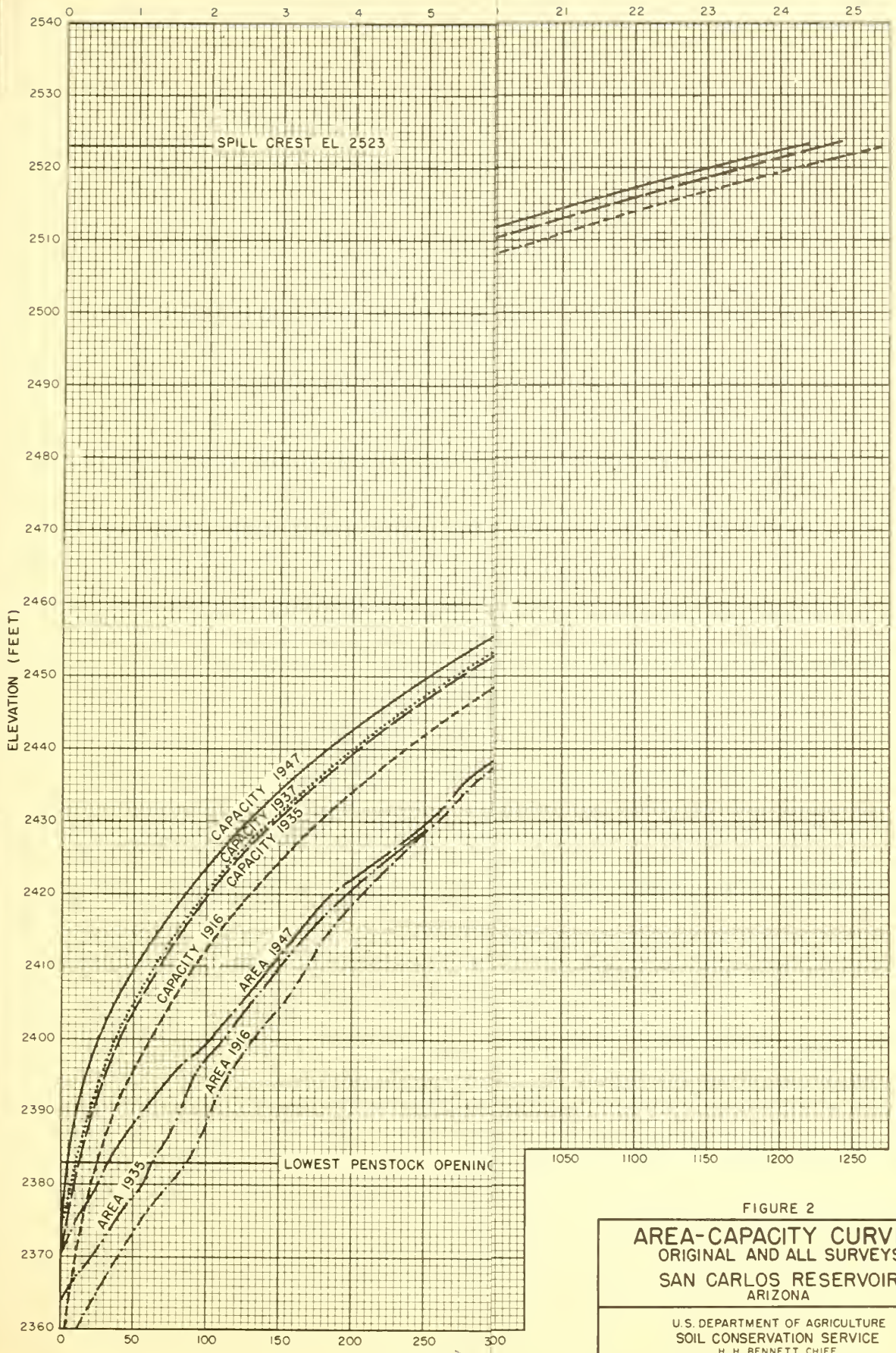

[34]

FIGURE 2

AREA-CAPACITY CURVES
ORIGINAL AND ALL SURVEYS
SAN CARLOS RESERVOIR
ARIZONA

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF
SOUTHWEST REGION CYRIL LUKER, DIRECTOR

MAY 1950

AREA IN THOUSANDS OF ACRES

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

SPILL CREST EL. 2523

ELEVATION (FEET)

2540 2530 2520 2510 2500 2490 2480 2470 2460 2450 2440 2430 2420 2410 2400 2390 2380 2370 2360

CAPACITY 1947
CAPACITY 1937
CAPACITY 1935
CAPACITY 1916
AREA 1947
AREA 1916
AREA 1935

LOWEST PENSTOCK OPENING EL. 2383

0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 1200 1250

CAPACITY IN THOUSANDS OF ACRE FEET

[34]

FIGURE 2

AREA-CAPACITY CURVES
ORIGINAL AND ALL SURVEYS

SAN CARLOS RESERVOIR
ARIZONA

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
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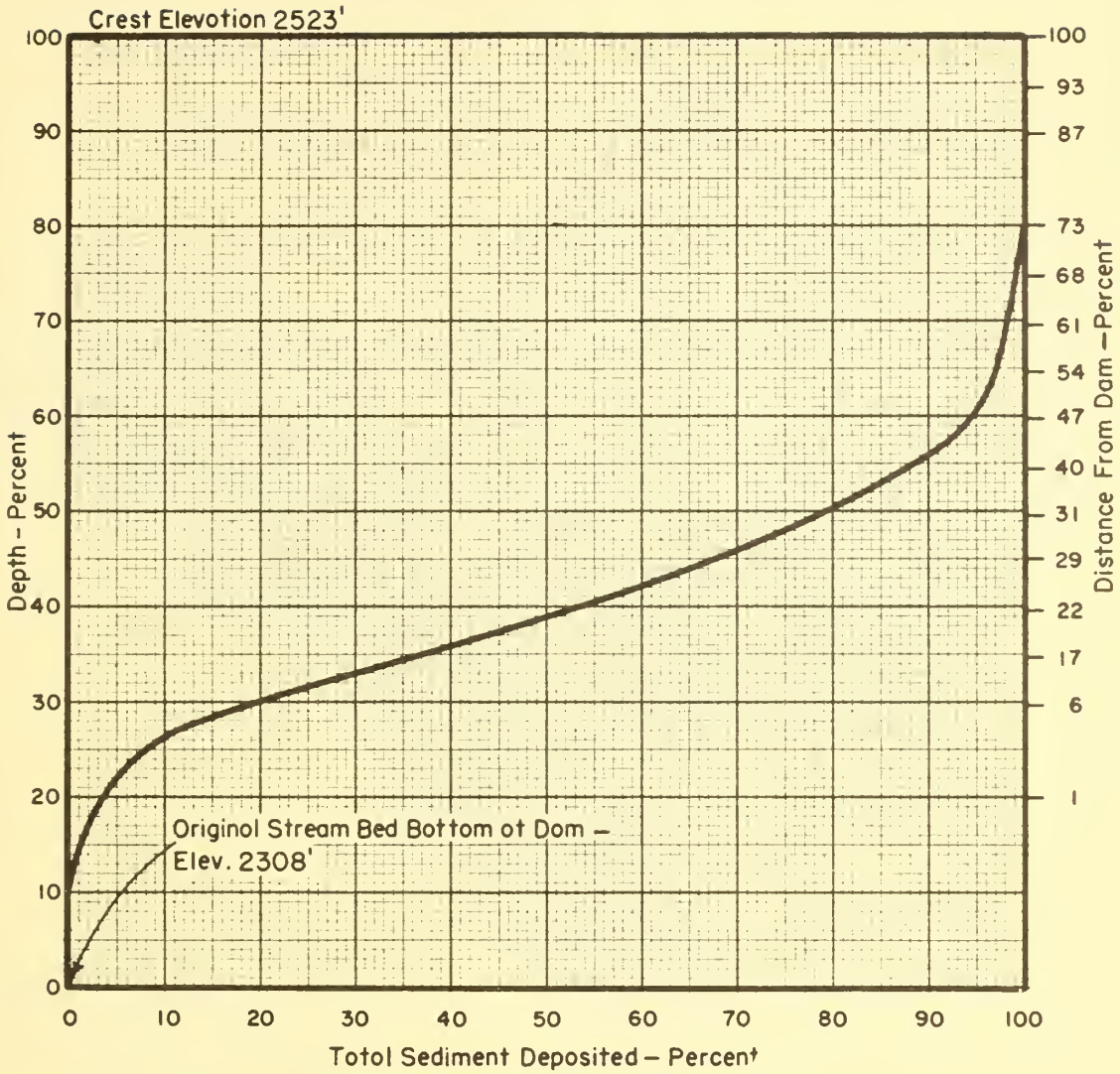

FIGURE 3

SEDIMENT DISTRIBUTION
ACCORDING TO DEPTH AND LENGTH OF RESERVOIR

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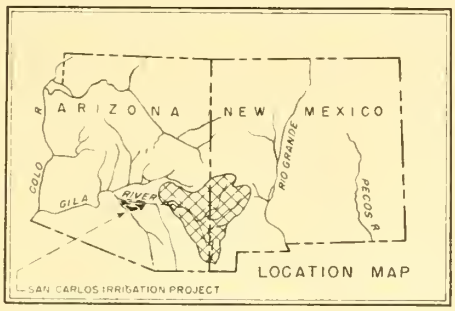

LEGEND

- Watershed Boundary
- Clased Basin Baundary
- Sub-drainage Basin Baundary

SEDIMENT PRODUCTION RATES

- Law
- Maderate
- High
- Very High

SUB-DRAINAGE AREAS

1 Headwaters
2 Cliff-Gila, N.M.
3 Duncan-Virden Valleys
4 San Francisca River
5 Eagle-Banita Creeks
6 San Siman Creek
7 Safford Valley ta Calva
8 San Carlos River

FIGURE 4

UPPER GILA RIVER WATERSHED

ARIZONA AND NEW MEXICO

SEDIMENT PRODUCTION AREAS

U S DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE

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MARCH 1948

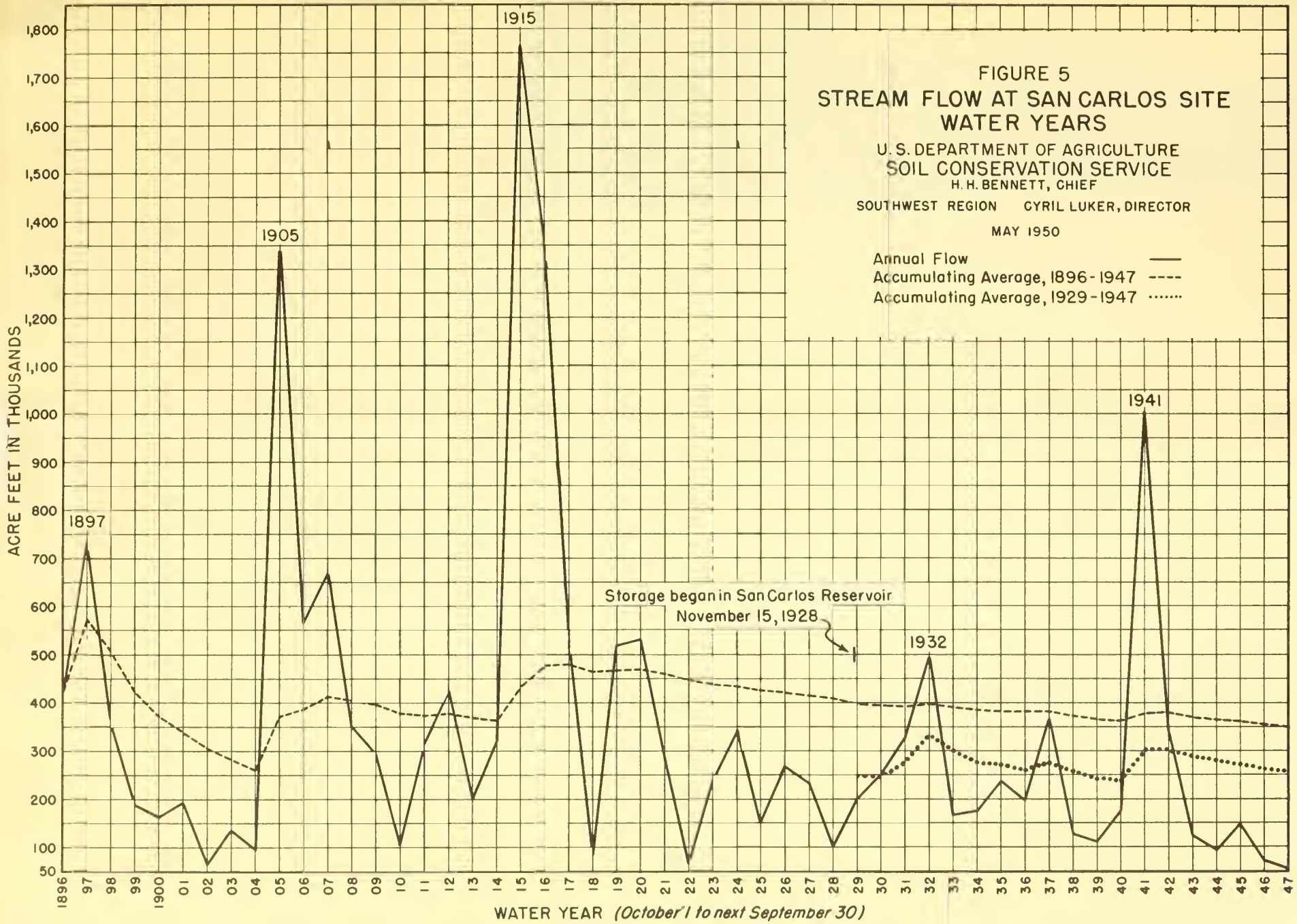
FIGURE 5
STREAM FLOW AT SAN CARLOS SITE
WATER YEARS
U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
H. H. BENNETT, CHIEF
SOUTHWEST REGION CYRIL LUKER, DIRECTOR
MAY 1950
Annual Flow
Accumulating Average, 1896-1947
Accumulating Average, 1929-1947
1915
1905
1941
1897
1932
Storage began in San Carlos Reservoir
November 15, 1928
ACRE FEET IN THOUSANDS
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
50
1896 97 98 99 1900 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
WATER YEAR (October 1 to next September 30)

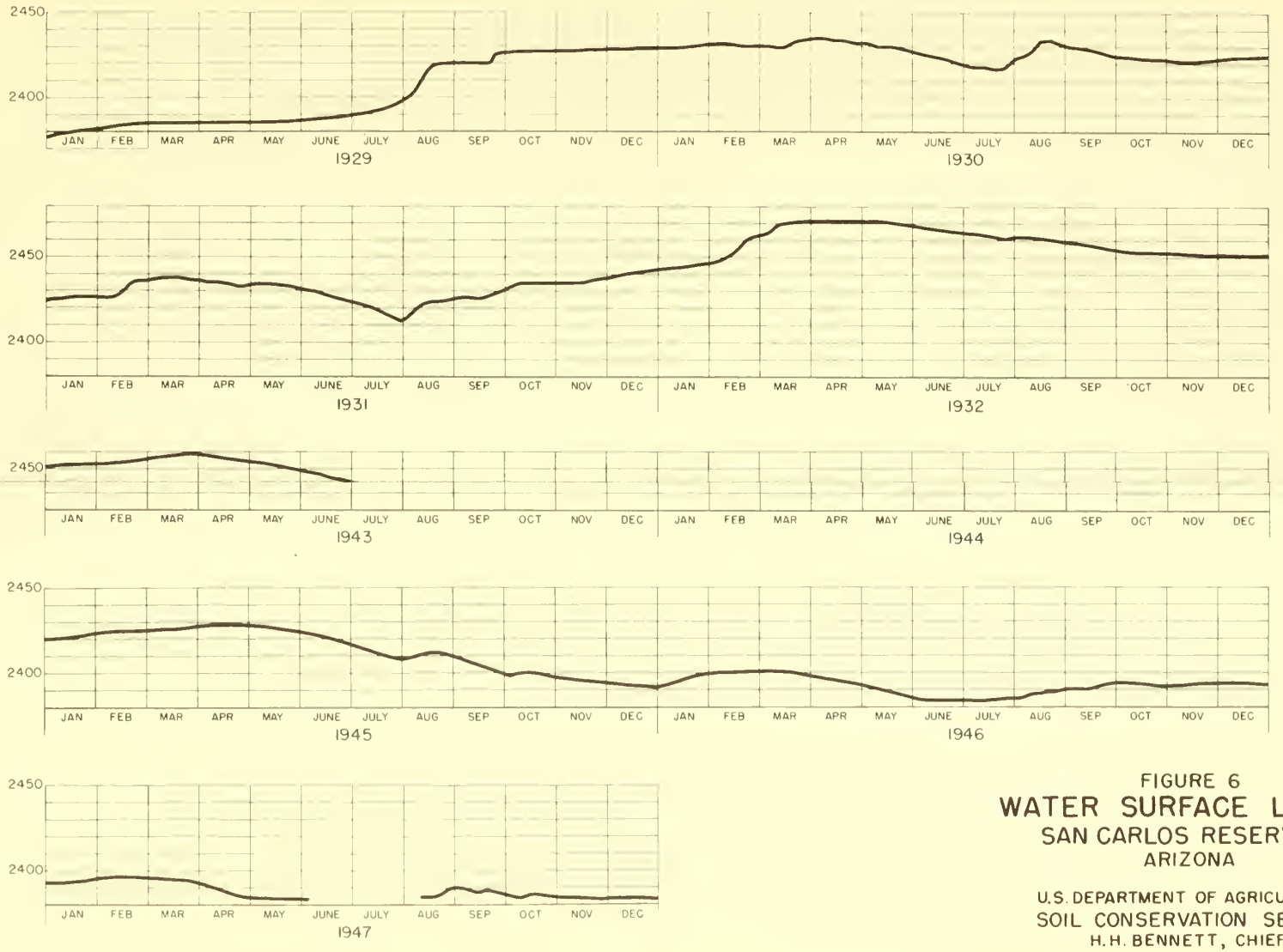

FIGURE 6

WATER SURFACE LEVELS
SAN CARLOS RESERVOIR
ARIZONA

U.S. DEPARTMENT OF AGRICULTURE
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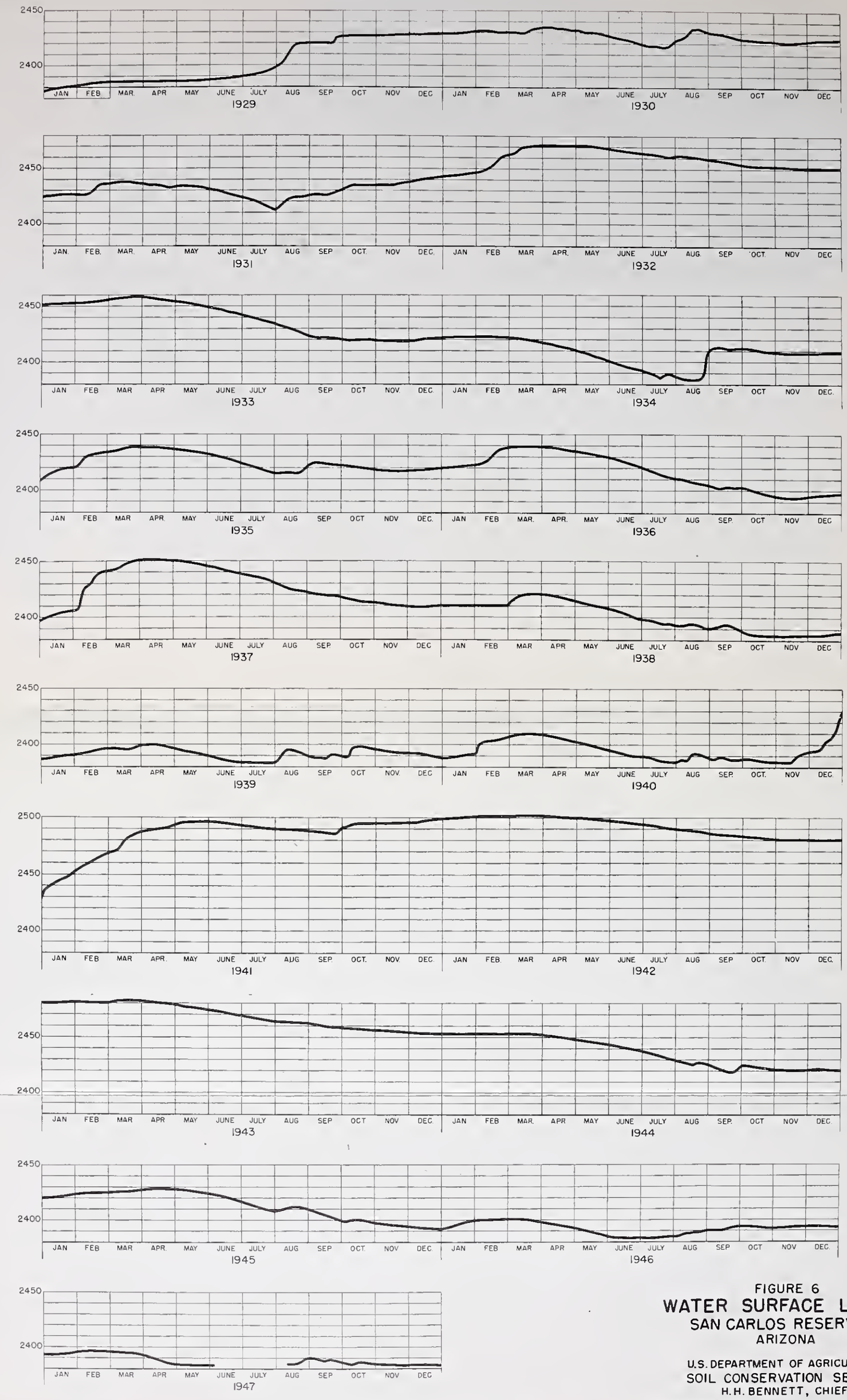
SOUTHWEST REGION CYRIL LUKER, DIRECTOR
MAY 1950

Data taken from Annual Reports, Gila Water Commissioner.



Data taken from Annual Reports, Gila Water Commissioner.

FIGURE 6

WATER SURFACE LEVELS

SAN CARLOS RESERVOIR

ARIZONA

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
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MAY 1950

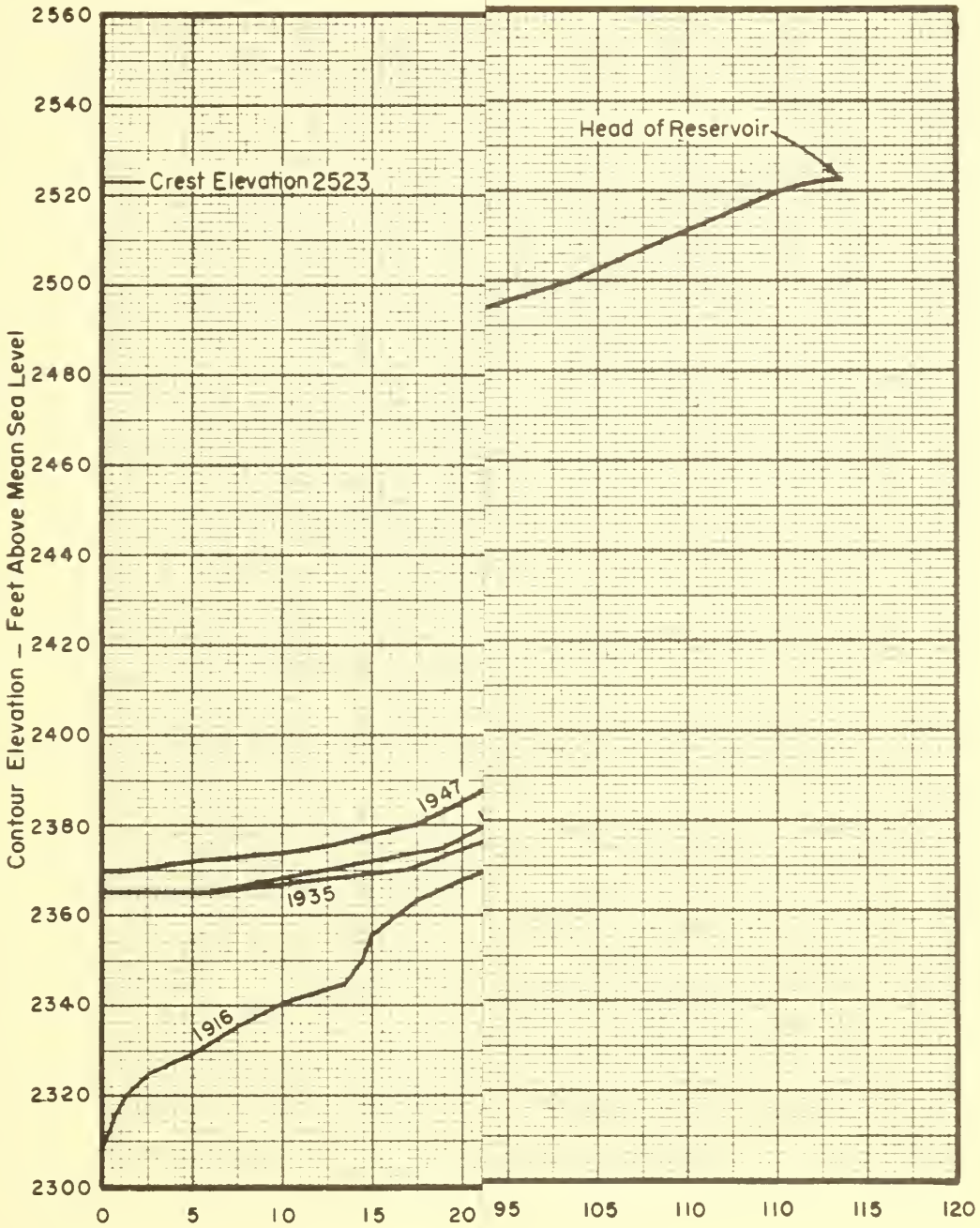

FIGURE 7

INAL PROFILES ALONG PRINCIPAL
OF SAN CARLOS RESERVOIR

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MAY 1950

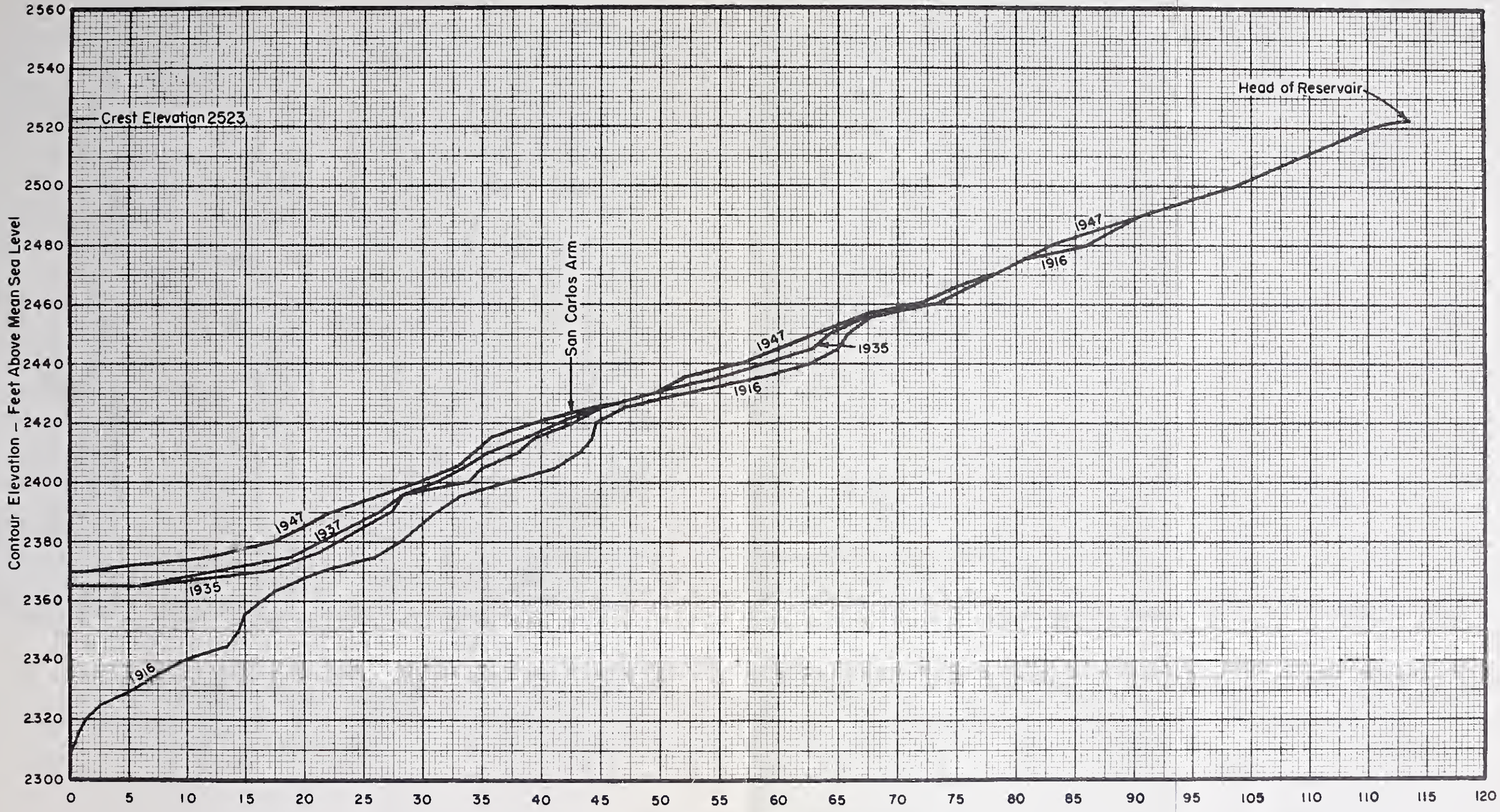

FIGURE 7

LONGITUDINAL PROFILES ALONG PRINCIPAL AXIS OF SAN CARLOS RESERVOIR

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SOIL CONSERVATION SERVICE
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SOUT ON CYRIL LUKER, DIRECTOR

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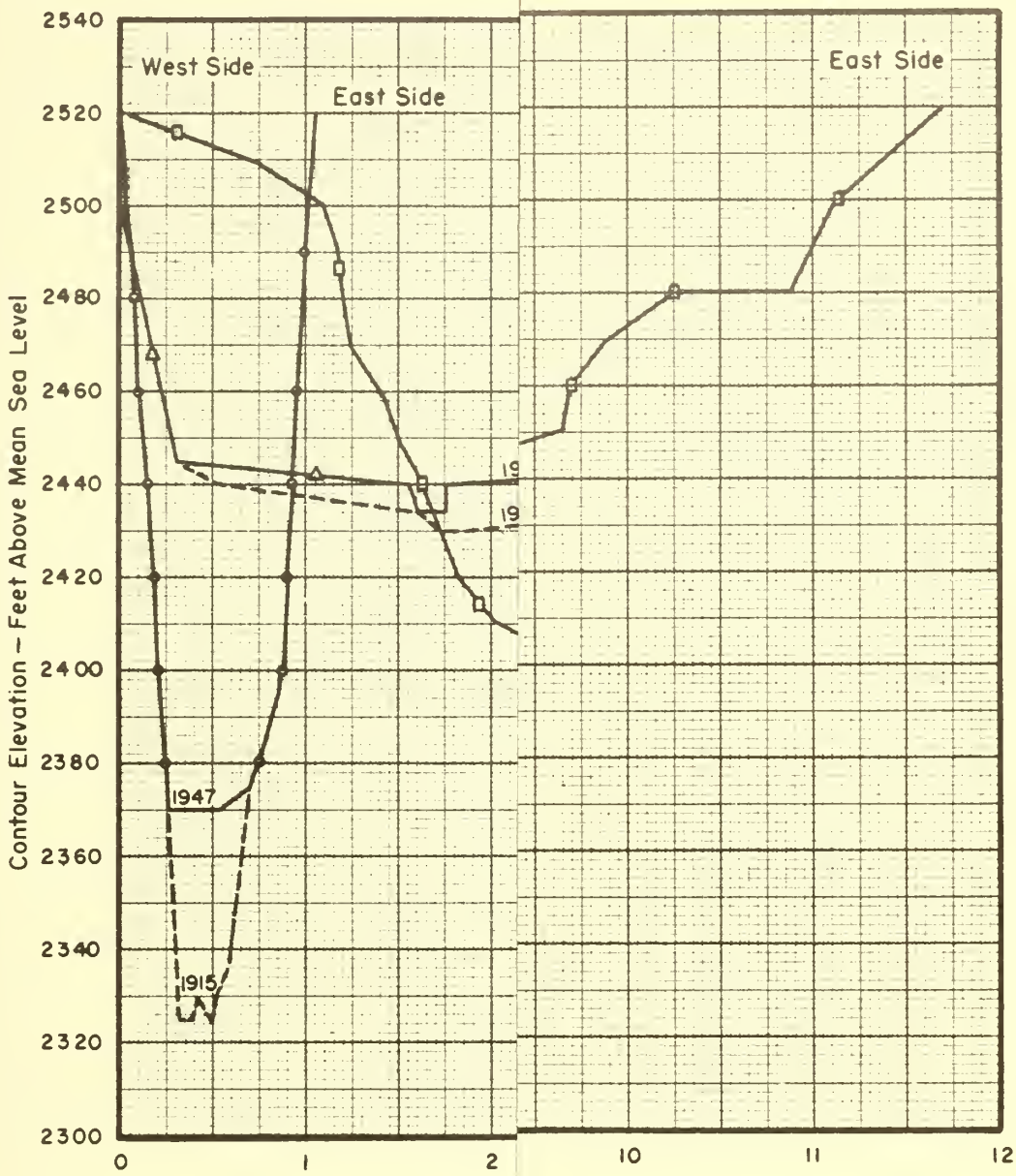

FIGURE 8

RANSVERSE PROFILES

CARLOS RESERVOIR 1915, 1947

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OIL CONSERVATION SERVICE

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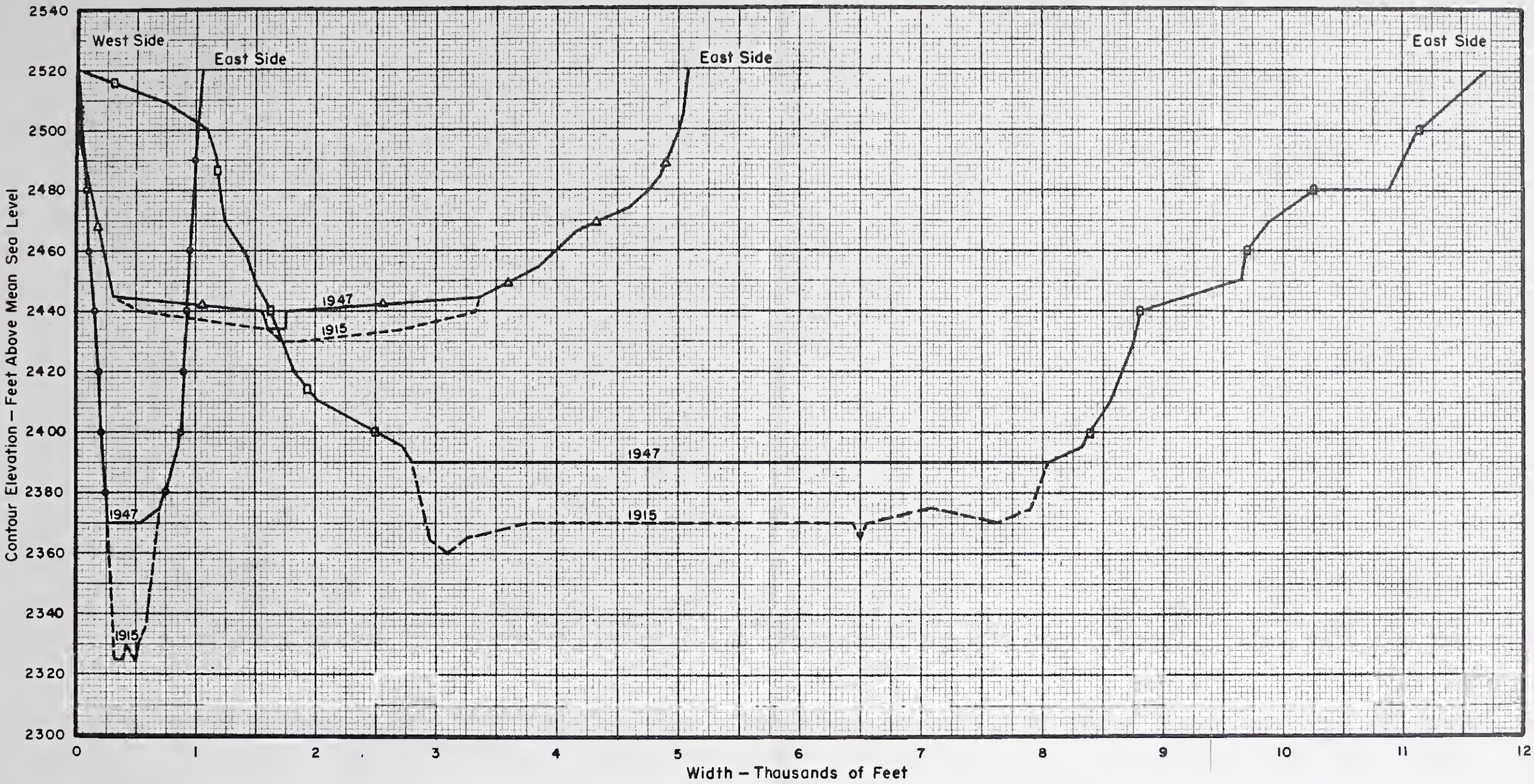
ON CYRIL LUKER, DIRECTOR

MAY 1950



Cross Section Neor Dam — 14+60 From Dom

Cross Section At Widest Part of Reservoir — 210+00 From Dom

Cross Section Uploke — 580+00 From Dom

FIGURE 8

TRANSVERSE PROFILES

SAN CARLOS RESERVOIR 1915, 1947

U. S. DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE

H. H. BENNETT, CHIEF

SOUTH[illegible]ON CYRIL LUKER, DIRECTOR

MAY 1950

AGR-SCS-BELTSVILLE, MD. 2115 MARCH 1951